Multifunction Radar Resource Management using Tracking Optimisation

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***Abstract*—In this paper we report on the relationship between track update intervals and track accuracy in a Multifunction phased array radar system. Strategies for selecting the update rate are highlighted and the degradation of performance as update rate reduces is demonstrated. It is shown that using suitable techniques considerable radar resources can be liberated for non-tracking tasks.**

I. INTRODUCTION

The advent of phased array radars with the capability to electronically steer the main beam has helped to overcome many of the problems and limitations inherent to traditional track-while-scan systems. Now the direction of the beam can be changed almost instantaneously so the control software is to a large extent free to decide when to illuminate each target. Also the time-on-target can be tailored to achieve the desired S/N ratio according to each specific track.

A Multifunction Radar (MFR) is equivalent to a suite of radars, sometimes employed for some applications such as air defence. To fulfil its purpose it performs several different functions which previously would have been undertaken by many different, dedicated radars. The exact functions that are undertaken are dependent upon the application, but, as a minimum, the multifunction radar will provide search coverage and concurrent tracking of multiple targets. With the capability to perform multiple functions within a single sensor comes drawbacks. In particular, the total radar time-budget from this single sensor must be shared between each of the functions. This means that radar time is at a premium and in many practical scenarios, less radar time is available than is ideally required. The development of radar techniques and tasks that are efficient in their use of radar time are thus crucial, and form the principal focus for this work.

This paper reports on a programme of study to explore the techniques and control algorithms needed to allow graceful modification of radar tracking task performance as a function of the time available to the radar and the performance it is attempting to achieve. The aim of this task is to maintain track, to the specified accuracy, whilst minimising the radar time budget to allow acceptable surveillance performance.

II. BACKGROUND

A. Multifunction Radar

A Multifunction Radar (MFR) combines the electronic steering of the antenna beam with the capability to use computer control to adaptively vary a range of parameters such as PRF, waveform coding, power and signal processing. This adaptive capability enables the MFR to replace a large number of conventional radars, since it is capable of performing volume surveillance, multiple target tracking, missile communications and aircraft support and navigation.

Thus the MFR attempts to substitute a number of other sensors, each of which dedicates all of its time to performing a specific function. Therefore the issue of time management is crucial if efficient utilisation of the MFR capabilities is to be achieved. This area has attracted intense research (e.g. [1]) and time management is the second of two most crucial factors in MFR design [2]:

- Choice of radar frequency, high enough to provide the narrow tracking beam, and low enough to permit rejection of clutter driving volume search modes.
- Budgeting of radar time to provide the dwell times necessary for clutter rejection in both search and tracking modes.

B. MFR Time Management

When working on time management, it is important to minimise the amount of sensor time required for each task. To achieve this, one needs to control the parameters employed for each specific dwell so that the performance of the MFR is best possible in relation to this dwell. Such parameters can be: the dwell time, the revisit interval, waveform coding, PRF, beam spacing, peak power, frequency, false alarm rate, and others. Parameter optimisation has been extensively investigated and rapidly becomes complex due to the multiple tradeoffs required. A simpler and effective alternative is to vary the update time in such a way to maintain sufficient tracking accuracy while freeing up the maximum radar time for other tasks. In this case the following factors need to be taken into account:

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14. ABSTRACT

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- Update rate can be varied in a fixed or dynamic mode.
- Update rate required is liable to be strongly target trajectory dependent.
- Different tracking filters may need to be employed adaptively in order to optimise the tracking performance/radar resource balance.

All these approaches critically depend on the behaviour of the target and environmental backscatter. As mentioned above, a range of different tracking filters may be required to be adaptively deployed in an operational scenario. This work has studied mainly the use of the Singer GH and GHK Kalman filters. The general Kalman filter was first published in 1960. It is a linear estimator solution to the concept of filtering discrete data in order to smooth a sequence of measurements and predict future kinematic data behaviour. The filter design has made resounding influences on further data filtering methods and is used particularly for radar target tracking purposes. The principles and method of the Kalman filter are explained well in the literature, e.g. [3], [4].

C. Varying Update Rate

A number of examples of variable update rate trackers have appeared in the literature [5]. In that work an alpha-beta tracker with constant α and β filter parameters and variable update interval was studied. The argument here is that in order to maintain a constant residual as the acceleration increases, the update time should be varied in inverse proportion to the square root of the resultant increase in residual error. Similar studies have been reported on alpha beta filters [6] and on the use of the Interacting Multiple Model (IMM) algorithm [7], [8].

III. METHODOLOGY

Two main methods of varying update time have been examined in this work. In addition we have defined a range of target trajectories to investigate these methods.

A. Variable Look / Look Away Strategies

This technique is a straightforward method of time management whereby a set time interval is set up comprised of a period of looking at the target followed by a period of looking away. When looking, the radar takes measurements of the target as usual and the tracking process is updated as such. When looking away, the radar is involved with other functions e.g. surveillance so the tracking process has to rely on the filter estimates to predict the target's activities.

This technique is used to ascertain the tracking performance for a given update time and with regards to various target trajectories. A wide range of time intervals and looking and looking away periods were examined for this purpose. It is a useful method for investigating the behavioural relationship between the tracker and the target,

Much research has been done on dynamically varying the update time while tracking in order to set resource time aside for use by other radar functions. The resource time required by the tracking process is related to the target manoeuvrings.

The algorithm used here provides a trade-off between keeping the estimation errors low while restricting the mean update time from becoming excessively small or excessively large.

B. Adaptive update time

The adaptive update time is calculated as follows:

1. The standard deviation of the measurement noise is calculated over the entire trajectory.

$$s = stddev(measurement\_noise) \tag{1}$$

After each estimation:

2. The residual error is normalised to remove the effect of the measurement noise [6]

$$e = \frac{abs(y_n - x_n)}{s} \tag{2}$$

3. The update time is recalculated using the 'cube-root filter' [7] as

$$t_{n+1} = \frac{t_n}{\sqrt[3]{e/\lambda}} \tag{3}$$

where $\lambda = 2.25$ according to evaluations by Shin.

4. The update time is rounded to a factor of the sampling interval T, where in this case T=1s.

$$t_{n+1} = round.(\frac{t_{n+1}}{T}) \tag{4}$$

5. To limit the update time to an acceptable interval, t is restricted to design-specified minimum and maximum values [6]. In this case, $1 \leq t_{n+1} \leq 4$ s.

C. Target Trajectories

Since this methodology is liable to be very dependent on target manoeuvre we have examined a range of target trajectories involving constant and changing speed and acceleration. In this paper we report on results obtained using three trajectories. One simulating a sea skimming target and two simulating flight trajectories of an aircraft. Details of these trajectories are as follows:

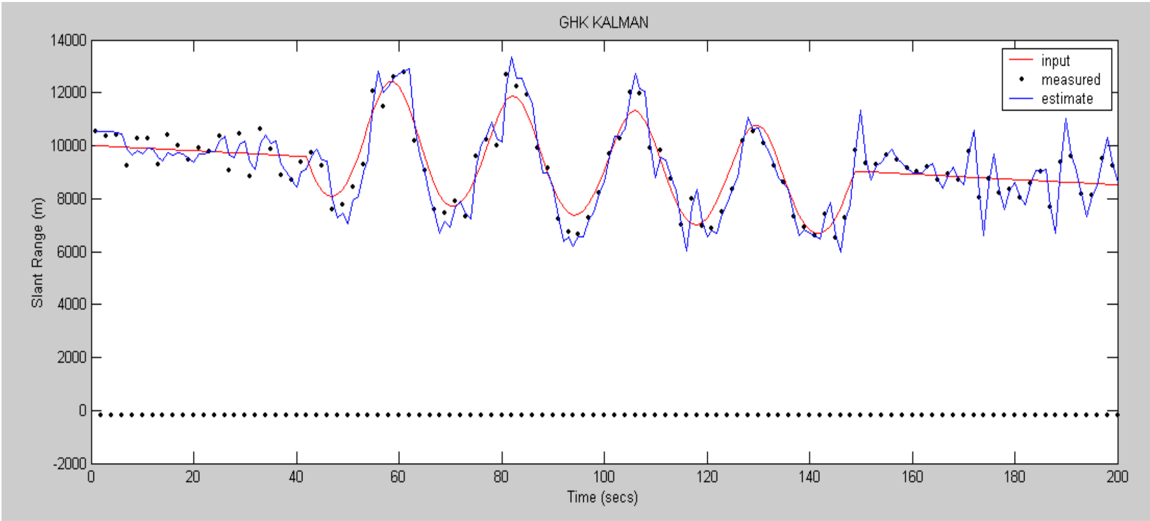

Fig. 1. GHK Kalman Constant Time Response to Trajectory 3 for a constant update rate.

Trajectory 1: Constant speed (300 m/s) straight line path.

Trajectory 2: A target moving in a curved line consisting of changing acceleration from 1s to 40s, acceleration to 150s then changing acceleration again to 200s.

Trajectory 3: Describes a target moving at a constant speed while making rapid manoeuvres simulated by a sinusoidal pattern.

While not necessarily representative of true target behaviour these trajectories serve to illustrative tracking accuracy trends for a range of situations.

In the case of the changing acceleration profile (trajectory 3), the GH filter does not adjust to the acceleration or changing acceleration but merely fits straight lines into the curves. The GHK filter behaves as before but becomes highly reactive to the changing acceleration at the end of the curve.

For the sine wave profile of trajectory 4, the GH filter behaves as a low pass filter through the trajectory manoeuvres while the GHK filter follows the manoeuvres easily but is susceptible to the positional noise (Fig. 1). The probability error seems to have little effect in either case. These results are broadly in line with expectation and verified the validity of the filter simulation developed.

Two sources of noise were added to the target trajectory data to make the simulation more realistic:

- Positional error: A random range error of up to 1000m is added to each measurement of the range trajectories to represent radar measurement error.
- Probability error: A probability error is included to take into account the S/N ratio, azimuth and elevation errors while only tracking in one dimension. Probability errors in the range 0-50% were used in this work.

The trajectory data was fed in to the simulation in the form of range/height data as a function of time.

IV. Results and Analysis

A. *Filter Model Validation*

A simulation was written in MATLAB for the GH and GHK Kalman filters. To verify the simulator models, these were initially run on a selection of the trajectories using a constant update rate (2 s) to verify their expected behavior.

These tests showed that the constant speed trajectory (1) is easily fitted by the GH filter after an initial settling period. The GHK filter is however designed to fit to quadratic trajectories and in the case of the constant velocity trajectory 1 interprets the added positional error as target acceleration adding jitter on the estimated data.

B. *Look/Look Away Method*

As described previously, this technique is a straightforward method of time management whereby a set time interval is set up comprised of a period of looking followed by a period of looking away.

Fig. 2 illustrates an example of this technique where the time interval (window) is 8 seconds long, the looking period (look) lasts 4 seconds and the looking away period lasts the other 4 seconds. The figure shows that measurements are taken in the look period where they contribute to the filtering process. In the look away period, the measurements are not used and are represented as values at zero slant range. While looking away, the filter is unaware of target manoeuvres and cannot be as reactive as expected. Also while looking away, the filter relies on its estimated values and is influenced by positional error changes.

The Kalman filters used here are very dynamic and expect quick target manoeuvres and therefore respond to the positional noise as if it is a target manoeuvre. This technique was tested by comparing the standard deviation of the residual error results for a range of look times and window sizes. In all these tests, the positional error is a maximum of 1000 m.

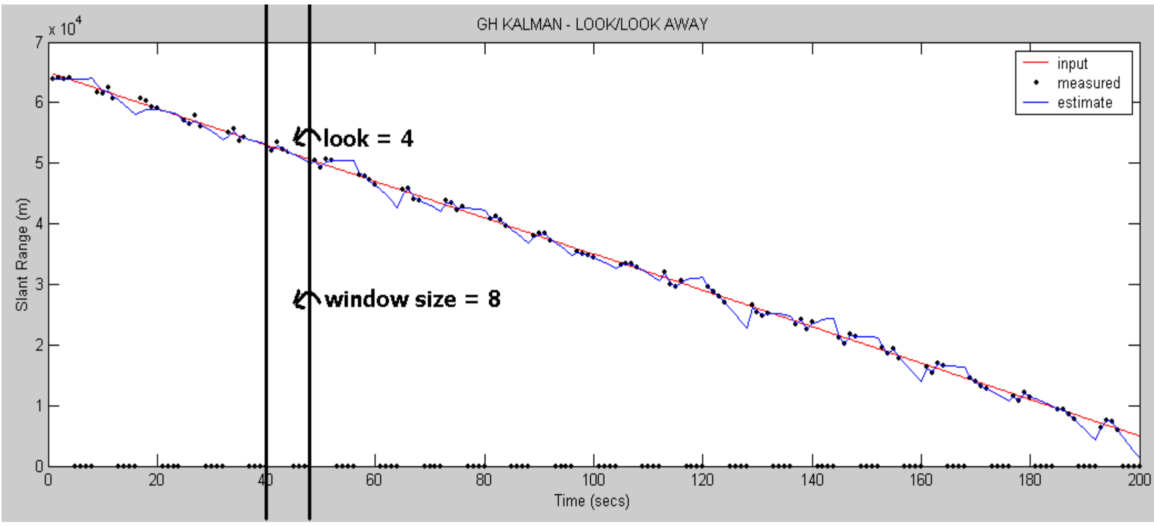

Fig. 2. Illustration of Look / Look Away Technique

Fig. 3(a) shows the GH Kalman filter look / look away response to trajectory 1 by illustrating the residual error vs window size for various look times. Fig. 3(b) shows the response for the GHK Kalman filter.

(a)

(b)

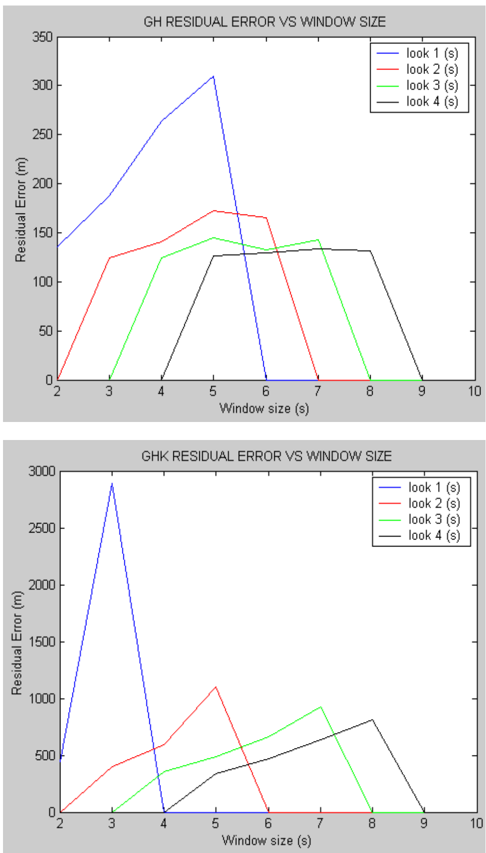

Fig. 3. GH (a) and GHK (b) Kalman Look / Look Away Response to Trajectory 1

These figures illustrate the following points:

- The GH filter tracks trajectory 1 with relatively low residual errors compared to the GHK filter.
- The residual errors decrease as the look time increases as is expected.
- Look times of 3s or more give the filter a better chance at tracking the trajectory.
- Large window sizes leave more room for error.

The above analysis was repeated for trajectory 2 to examine the effect of changing speed and acceleration. A summary of this data is plotted in Fig. 4.

(a)

(b)

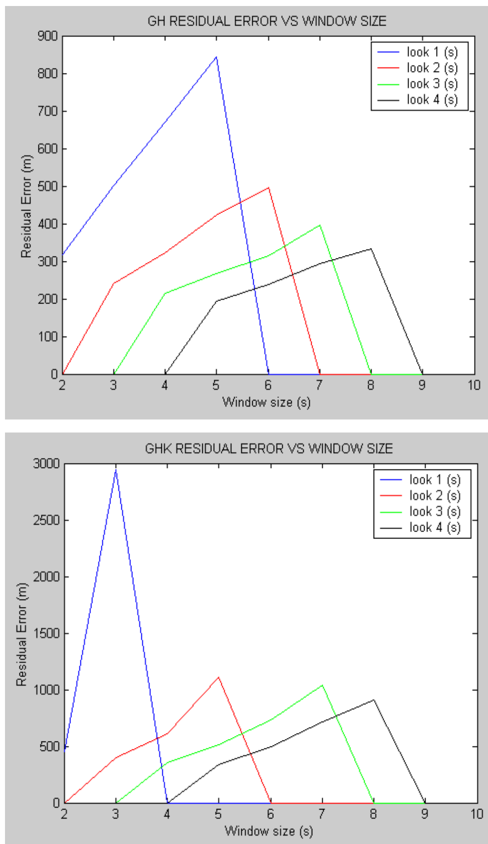

Fig. 4. GH (a) and GHK (b) Kalman Look / Look Away Response to Trajectory 2

These results show that the GH filter produces residual errors of triple the size for trajectory 2 than those for trajectory 1 whereas errors for the GHK filter are similar for both trajectories. The GHK copes much better with the changing acceleration as expected, even with substantial "look away" times. Once again for larger window sizes, longer look away times can be tolerated while maintaining reasonable error levels. For trajectory 3, the same simulation analysis shows (Fig. 5) that the residual errors of the GH

filter for trajectory 3 have improved over those of trajectory 2 as trajectory 3 does not change much in slant range. The residual errors of the GHK filter are the lowest measured as the filter tries to follow the trajectory manoeuvres.

(a)

(b)

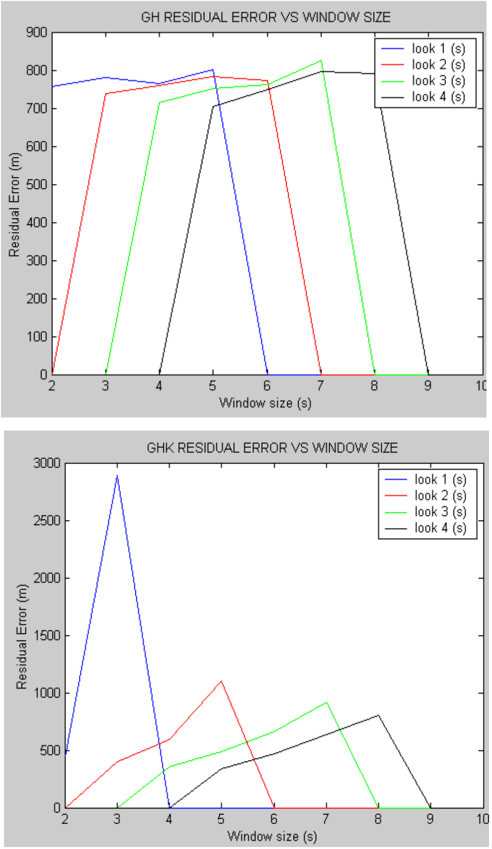

Fig. 5. GH (a) and GHK (b) Kalman Look / Look Away Response to Trajectory 3

C. *Variable Update Rate*

In this case, the update rate is adaptively altered to match the target manoeuvre while maintaining a constant residual error. This is illustrated in Fig. 6. for trajectory 3. Since this method works on the basis of setting the required residual error, we have plotted residual error against a probability error varied between 0 and 20% (Fig 7).

(a)

(b)

(c)

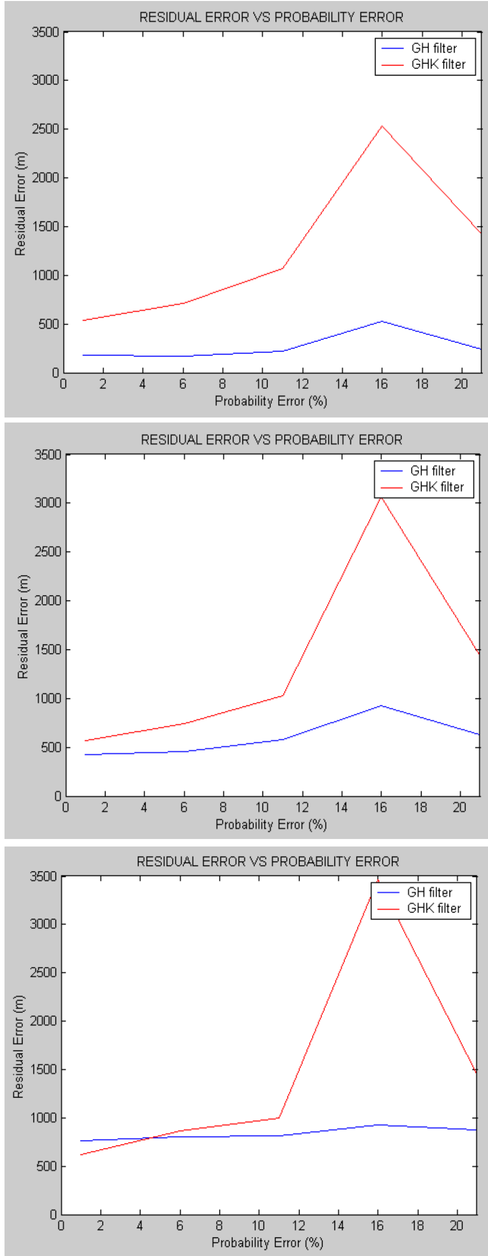

Fig. 7. Residual error versus probability error using the variable update method for trajectories 1 (a), 2 (b) and 3 (c) respectively.

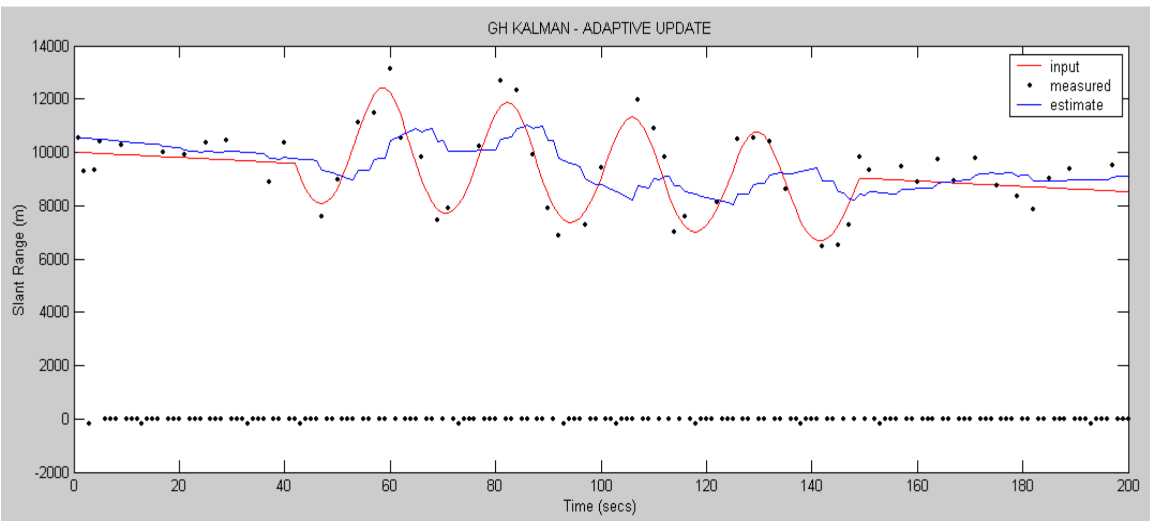

Fig. 6. Illustration of variable update time method for Trajectory 3. The dots at the bottom indicate "look away" points. It can be seen that looks are more frequent during more extreme target manoeuvres.

From these results it can be seen that the GH filter produces similar results to constant time tracking while the GHK filter is kept under better control by the adaptive time technique especially when the trajectory changes. Thus the adaptive method is better suited to a mix of trajectory types while still enabling significant radar time saving over a constant update rate.

The actual radar time used varies according to the target trajectory profile. For the particular trajectories and errors assumed in this study we find that positional error can be generally contained to within a maximum of 100 - 1000m except in the case where the GHK filter is dropped out by noise.

The radar time used to obtain these results varies between 25% and 75%. These results are quantified in Table 1. A substantial saving of radar resources is thus possible by using these methods.

Table 1. Adaptive update times for GH (a) and GHK (b) Kalman filters. These values are relative to a constant update rate of 1 second.

(a)

PROBABILITY ERROR (%)	ADAPTIVE UPDATE TIME GH traj1	GH traj2	GH traj3
	AVE ADAPTIVE TIME (s)		
0	3.6090	3.4400	3.0380
5	3.5965	3.4565	3.2675
10	3.6210	3.5025	3.3870
15	3.7010	3.6320	3.5465
20	3.6635	3.5790	3.5075

(b)

PROBABILITY ERROR (%)	ADAPTIVE UPDATE TIME GHK traj1	GHK traj2	GHK traj3
	AVE ADAPTIVE TIME (s)		
0	2.8835	3.0000	2.8660
5	2.9440	3.0150	2.9940
10	3.1080	3.1165	3.0840
15	3.2740	3.2880	3.2530
20	3.1495	3.1895	3.2095

V. CONCLUSIONS

- A simulation using fairly realistic noise and positional error data shows that GH and GHK Kalman filters can maintain tracking accuracy for most target trajectories if the correct filter matching is used. If not matched, then the tracking predictions become inaccurate and, depending on how reactive the filter is, can escalate to the point of dropping the track. Trajectories examined included constant velocity, constant acceleration and changing acceleration. Actual velocities and manoeuvres used were representative of a range of real target scenarios.
- It was also shown that the filters can still maintain reasonable tracking accuracy without constant updates using a simple look/look away strategy . The settings chosen for the look/look away times method needs to be chosen carefully in relation to the target trajectory to optimise time resource saving.
- Using a more sophisticated adaptive update technique has been shown to be better suited to a mix of trajectory types while still enabling significant radar time saving over a constant update rate..
- With these models it was shown that radar resource time can be liberated even when the filter does not match the trajectory correctly. Up to 75% of radar resource time could be freed for non-tracking tasks by these methods
- The exact amount of time that can be released is highly scenario dependent. In cases of highly manoeuvring targets there may be little or no gain of radar time possible without losing track accuracy or dropping the track altogether.
- Further tests are planned using a more realistic radar scenario. Factors such waveform coding, PRF, beam spacing, peak power, frequency, false alarm rate and clutter need to be considered.

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